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13. ABSTRACT *(Maximum 200 words)*

Much military-specific manufacturing involves complex, special purpose electro-optical and electro-mechanical systems where development and fabrication costs can't be spread across high-volume civilian products. Computer vision systems are an important enabling technology for the cost effective, flexible automation needed to produce such systems. Our work focuses on the creation of accurate and usable geometric models of manufactured objects. Such models allow for update of manufacturing processes and easy modification of existing parts. They are also central to emerging technologies such as simulation-based design and virtual prototyping.

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=== Final Report ===

ORGANIZATION: University of Utah

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TITLE OF EFFORT: Sensing Strategies for Advanced Manufacturing

SUBTITLE:

Building object models from sensed data in a manufacturing environment.

EXECUTIVE SUMMARY PARAGRAPH:

Much military-specific manufacturing involves complex, special purpose
electro-optical and electro-mechanical systems where development and
fabrication costs can't be spread across high-volume civilian
products. Computer vision systems are an important enabling technology
for the cost effective, flexible automation needed to produce such
systems. Our work focuses on the creation of accurate and usable
geometric models of manufactured objects. Such models allow for update
of manufacturing processes and easy modification of existing parts.
They are also central to emerging technologies such as simulation-based
design and virtual prototyping.

OBJECTIVE:

The objective of the project is to develop better methods for using
image understanding technologies in a manufacturing environment.
Particular emphasis is being given to the creation of object models
>from sensed data to support modern design and manufacturing systems.
Our immediate goal is to be able to generate a full function CAD model
of an existing, milled part with an accuracy within normal variations
in the NC machining process

APPROACH:

Reverse engineering of mechanical parts requires extraction of
information about an instance of a particular part sufficient to
replicate the part using appropriate fabrication techniques. This is
important in a wide variety of manufacturing situations, since
functioning CAD models are often unavailable or unusable for parts
which must be duplicated or modified. Computer vision techniques
applied to 3-D data acquired using non-contact position digitizers have
the potential for significantly aiding the process. Serious challenges
must be overcome, however, if sufficient accuracy is to be obtained and
if models produced from sensed data are truly useful for manufacturing
operations. Our key innovation is to use geometric representations
natural to the manufacturing process. This results in significant
improvements in accuracy and usability.

PROGRESS:

The project investigated the application of innovative image

understanding and related 3-D sensing technologies to selected tasks relevant to advanced manufacturing. The aim was to gain substantial advantages in effectiveness and usability by developing sensing strategies within the context of the complete design and manufacturing process.

High-Precision, Constraint-based Reverse Engineering of Mechanical Parts:

CAD models of existing parts may be unavailable because other design techniques were used to create the part, the original CAD model is unusable for whatever reason, shop floor modifications were made to tooling, or use of the original CAD model is prohibited due to legal, proprietary, or technical reasons. Part-to-CAD reverse engineering allows up to date NC fabrication plus easier modification of the design. Current demand for reversed engineered CAD models ranges from the aircraft to automotive industries.

Existing approaches to part-to-CAD reverse engineering are limited to reconstructing the low-level surface geometry of the part, but cannot support modern, feature-based design systems. As a result, automatic process planning is difficult and modifications of the model are almost impossible. Our innovation is to extract high-level manufacturing features from 3-D sensed data of a machined part. Domain-specific information can be used to increase the accuracy of models reconstructed from sensed data. Meaningful measures of modeling accuracy require domain-specific information about the relevance and intent of geometric features.

Calibrated Image Generation:

The development of benchmarks for measuring progress on IU for manufacturing presents both challenges and opportunities compared to other areas of image understanding research. High positional accuracy is usually required. As a result, methods can be effectively evaluated only if precise ''ground truth'' data about visible objects used for testing is available.

Images of objects with known shapes in known positions, taken with calibrated cameras, were made available in order to provide test data for image understanding systems performing classification, pose estimation, and stereo surface reconstruction operations.

Sensor Modeling:

An approach called instrumented sensor systems has been developed to allow the modeling of diverse sensors and data formats in order to analyze the tradeoffs between efficiency and robustness. The overall goals are to model and simulate sensor systems, evaluate alternative sub-systems, and to allow crucial on-line monitoring of sensor systems. We have looked into the application of this approach in virtual environments which require the simulation of virtual sensors that must behave like their physical counterparts. In addition, we applied this framework to the analysis of multisensor systems in mobile robotics and in wide area distributed sensor systems.

As reported earlier, REFAB, a prototype feature-based reverse engineering system has been developed and demonstrated on parts of moderate complexity. We have quantitatively evaluated the accuracy of the models that we have obtained. This was done by using parts from our "Hard-Copy Benchmark" for which we had access to the original CAD models. Instances of these parts were carefully machined out of aluminum using a 3-axis NC mill. Surface points on the parts were measured using a non-contact laser digitizer.New CAD models for

each part were generated using the REFAB system. Finally, the geometric differences between the original and recovered models were computed.

We have developed an optimal sensing strategy for recovering vertical walls with two spread-beam sonar sensors. Experimental results have demonstrated the effectiveness of the technique.

We created a data set consisting of imagery and sufficient collateral information to support the quantitative evaluation of computer vision methods for three sorts of generic tasks: (1) model-based object recognition, (2) model-based pose estimation and (3) depth reconstruction from binocular stereo.

PRODUCTS: none.

ACCOMPLISHMENTS:

Installation of an "industrial-strength" sensing facility to provide accurate, calibrated 3-D data of mechanical parts.

Quantitative analysis of sensor performance.

Significant improvements in accuracy of CAD models generated from sensed data. Primary feature properties are now being recovered with a precision comparable to that resulting from the normal CAD/CAM driven NC milling process.

Involvement with companies involved in reverse engineering to facilitate commercialization of technology we have developed.

PUBLICATIONS:

(papers marked with a * can be accessed using the URL "http://www.cs.utah.edu:80/projects/robot/sam/papers.html".)

T.M. Sobh, J.C. Owen, M. Dekhil, and T.C. Henderson ``Industrial Inspection and Reverse Engineering,'' Computer Vision, Graphics and Image Processing, special issue on Model-Based Vision, to appear.

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T.M. Sobh, T.C. Henderson and F. Zana, ``A Unifying Framework for Tolerance Analysis in Sensing, Design, and Manufacturing,'' IEEE Conference on Robotics and Automation, May, 1995.

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J.C. Owen, P.-P.J. Sloan, W.B. Thompson and T.C. Henderson, ``Interactive Feature-Based Reverse Engineering of Mechanical Parts,'' Proceedings of the ARPA Image Understanding Workshop, November 1994.

W.B. Thompson and J.C. Owen, ''Hard-Copy Benchmark Suite for Image Understanding in Manufacturing,'' Proceedings of the ARPA Image Understanding Workshop, November 1994.

T. C. Henderson, T. M. Sobh, F. Zana, B. Bruderlin, and C. Hsu, ''Sensing Strategies Based on Manufacturing Knowledge'', Proceedings of the ARPA Image Understanding Workshop, November 1994.

T.C. Henderson, ''Industrial Inspection and Reverse Engineering,'' Proceedings of the CAD-Based Vision Workshop, Feb., 1994.

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